

Dark Matter and IceCube Neutrinos

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Summary. — We show that the excess of high energy neutrinos observed by the IceCube collaboration at energies above 100 TeV might originate from baryon number violating decays of heavy shadow baryons from mirror sector, which in turn constitute Dark Matter. Due to tiny mixing between mirror and ordinary neutrinos, it is possible to explain the specific features of the IceCube events spectrum.

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Discovery of high-energy neutrino events by the IceCube Collaboration [1] opened a new era of experimental high-energy neutrino astrophysics. Recently the collaboration published the three year data collected between 2010 and 2013, containing 37 candidate in the energy range from 30 TeV to 2 PeV. While the number of events with energies below 100 TeV or so is compatible with the background expectations, there is an evident excess of the events with $E > 100$ TeV or so. On the other hand, no events were observed in the gap between 400 TeV and 1 PeV, but three most energetic shower events emerged at the end of the spectrum with energies 1.04 PeV, 1.14 PeV and 2.0 PeV where the atmospheric background is practically vanishing. On the other hand, the spectrum is apparently cut off at energies larger than about 2 PeV. The gap in the energy spectrum is difficult to explain in known models of high-energy neutrinos of astrophysical origin.

The model that may explain such a spectrum was suggested in ref. [2]. Here we present main guidelines of this model. Nowadays it becomes popular the idea that dark matter of the universe can emerge from a parallel gauge sector, with particles and interactions sharing many similarities with ordinary particle sector. Such a shadow sector would contain particles like quarks which form composite baryons, as well as leptons and neutrinos which are all sterile for ordinary gauge interactions. In particularly interesting example is represented by so-called mirror world [3], which has the content of particles and interactions exactly identical to that of ordinary sector, with the same gauge and Yukawa coupling constants. Taking into consideration also attractive possibilities for particle physics beyond the Standard Model related to supersymmetric grand unified theory (SUSY GUT), one can consider that at higher energies both ordinary and mirror sectors are presented by identical GUTs, e.g. $SU(5)$ and $SU(5)'$ or $SU(6)$ and $SU(6)'$, which

in both sectors break down to their Standard Model subgroups $SU(3) \times SU(2) \times U(1)$ at the scale $M_G \sim 10^{16}$ GeV. However, following refs. [4, 5], one can assume that later on the symmetry between two sectors is broken so that the electroweak symmetry breaking scale V in mirror sector is much larger than than in the Standard Model, $v = 174$ GeV. Namely, if $V \sim 10^{11}$ GeV, then the lightest shadow baryons should have mass order few PeV. Due to baryon violating GUT gauge bosons, they decay with $\tau_{\text{dec}} \sim t_U$ producing energetic shadow neutrinos which oscillate into active neutrinos (with oscillation probabilities $\sim 10^{-10}$ or so) transferring their spectrum to the latter.

Let us consider, for simplicity, a supersymmetric grand unification theory $SU(5) \times SU(5)'$.⁽¹⁾ Consider a situation when in both sectors the GUT symmetries are broken at the scale $M_G \simeq 2 \times 10^{16}$ GeV, $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$ and $SU(5)' \rightarrow SU(3)' \times SU(2)' \times U(1)'$. Below this scale our sector is represented by MSSM with chiral superfields of quarks $q_i = (u, d)_i$, u_i^c, d_i^c and leptons $l_i = (\nu, e)_i$, e_i^c , $i = 1, 2, 3$ being family index, and two Higgs superfields h_1, h_2 . As for parallel sector we have the similar particle content, quarks $Q_i = (U, D)_i$, U_i^c, D_i^c , leptons $L_i = (N, E)_i$, E_i^c , and two Higgses H_1, H_2 . At the scale $\mu = M_G$ all gauge coupling constants are equal and the Yukawa couplings have the same pattern for ordinary and shadow fermions:

$$(1) \quad (Y_{ij}^e l_i e_j^c h_1 + Y_{ij}^d q_i d_j^c h_1 + Y_{ij}^u q_i u_j^c h_2) + (Y_{ij}^e L_i E_j^c H_1 + Y_{ij}^d Q_i D_j^c H_1 + Y_{ij}^u Q_i U_j^c H_2)$$

As for the neutrinos, their masses emerge from the following $D = 5$ operators [4]:

$$(2) \quad \frac{\alpha_{ij}}{M} (lh_2)(lh_2) + \frac{\alpha_{ij}}{M} (LH_2)(LH_2) + \frac{\beta_{ij}}{M} (lh_2)(LH_2)$$

where M is an effective scale of the order of Planck scale M_{Pl} [5]. The first two terms give the Majorana masses respectively to ordinary neutrinos $\nu_{e,\mu,\tau}$ and their shadow (sterile) partners while third term induces the mixing between ordinary and shadow neutrinos.

Below GUT scale, the gauge coupling constants of two sectors, respectively $g_{3,2,1}$ and $g'_{3,2,1}$ evolve down in energies in both sectors in the same way (see Fig. 1). For ordinary sector we follow to the standard paradigm. Supersymmetry is broken at the scale $M_S \sim 1$ TeV, the Higgses are not protected anymore to be massless and they get VEVs $v_1 = v \cos \beta$, $v_2 = v \sin \beta$, where $v = 174$ GeV, which induce the electroweak symmetry breaking and generate the fermion masses.

As for parallel sector, let us assume now that mirror symmetry between two sectors is spontaneously broken in the following way. Imagine that supersymmetry is broken in shadow sector at the scale $M'_S \sim 10^{11}$ GeV, supposedly due to non-zero F or D terms of some auxiliary fields, so that shadow scalars, including squarks and leptons as well as Higgs doublets H_1 and H_2 acquire soft masses order M_S .⁽²⁾ Respectively shadow Higgses Get VEVs $V_1 = V \cos \beta'$ and $V_2 = V \sin \beta'$, and electroweak symmetry is broken at the scale $V \leq M'_S$. Therefore, the masses of shadow fermions are rescaled, modulo renormalization factors order 1, by a factor $\xi = V/v$ with respect to ordinary fermion

⁽¹⁾ As discussed in ref. [2], our proposal can be more nicely realized in SUSY $SU(6)$ theory [6] which gives natural solution to the so called hierarchy and doublet-triplet splitting problems by relating the electroweak symmetry breaking scale to the supersymmetry breaking scale $M_S \sim 1$ TeV and naturally explains the fermion mass spectrum.

⁽²⁾ Interestingly, if supersymmetry breaking is transferred to our sector via gravity or other Planck scale mediators, this would explain ordinary soft masses order $M_S \sim M_S^2/M_{Pl} \sim 1$ TeV.

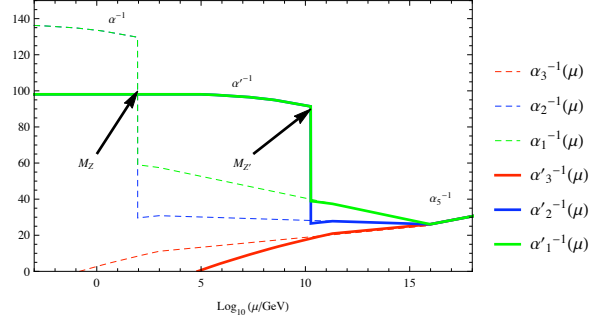


Figure 1. – Running of gauge couplings below the GUT scale, $\alpha_i = g_i^2/4\pi$ and $\alpha'_i = g_i'^2/4\pi$.

masses. Namely, taking $V/v = 10^9$ and assuming $\tan \beta' = \tan \beta$, by the RG running of gauge and Yukawa constants from the GUT scale down in energies, one obtains for the shadow electron mass $M_E \simeq 0.4$ PeV, $M_D \simeq 1.1$ PeV and $M_U \simeq 1.9$ PeV, against $m_e = 0.5$ MeV, $m_d \simeq 5$ MeV and $m_u \simeq 3$ MeV for ordinary electron and quarks. On the other hand, the RG evolution shows that the shadow QCD scale becomes $\Lambda' \sim 100$ TeV (c.f. $\Lambda \simeq 200$ MeV in ordinary QCD). Therefore, $\Lambda' \ll M_U, M_D$ and the shadow QCD looks like a rescaled version of our QCD without light quarks, but only with heavy quarks like c and b . Notice also that in shadow sector up quark U becomes heavier than the down quark D [2], and $M_{U,D}/\Lambda'$ is of the same order as $m_{b,c}/\Lambda$ in ordinary QCD.

The lightest state would appear to be a shadow Δ^- baryon of spin $3/2$, consisting of three down quarks D and having mass $M_\Delta \approx 3M_D = 3.3$ PeV. All states, containing up quark U , will be unstable against weak decays, $U \rightarrow D\bar{E}N$. As for mesons, the lightest pseudoscalar is shadow neutral pion π^0 consisting of $D\bar{D}$, with mass $M_0 \approx 2M_D = 2.2$ PeV, while the lightest vector meson $\rho^0(D\bar{D})$ is slightly heavier than π^0 . Charged Pion π^- as well as ρ^- -meson consisting of $D\bar{U}$ will have mass $M \simeq M_U + M_D = 3$ PeV, with ρ^- a bit heavier than π^- . All pseudoscalar and vector mesons have excited states with mass gap order Λ' between the levels, just like $c\bar{c}$ or $b\bar{b}$ states in ordinary QCD.

Now we come to the role of baryon violation and proton decay which is fundamental prediction of the GUTs. The heavy gauge bosons of $SU(5)$ with baryon violating couplings between quarks and leptons induce the decay of the lightest ordinary baryons (proton, or neutron bound in nuclei), with lifetime $\tau_p \sim M_G^4(\alpha_5^2 m_p^5)^{-1} \sim 10^{31}$ Gyr or so, where α_5 is $SU(5)$ coupling constant at the GUT scale $M_G \sim 2 \times 10^{16}$ GeV [7].

In the shadow sector, the similar couplings of GUT gauge bosons should destabilize the shadow baryon. However, taking into account that shadow Δ baryon is much heavier than the ordinary proton, $M_\Delta/m_p \sim 10^6$, its lifetime must be about 30 orders of magnitude smaller than the proton lifetime. Hence we get $\tau_\Delta \sim M_G^4(\alpha_5^2 m_\Delta^5)^{-1} \sim 10$ Gyr or so, with lifetime comparable to the age of the Universe $t_U = 14$ Gyr.

The principal decay mode of Δ baryon is in vector mesons, $\Delta^- \rightarrow \rho_a^- + \bar{N}_x$, where the neutrino state N_x is generically a superposition of shadow neutrino flavor eigenstates. However, taking into account the active sterile mixing $\sim \beta v/\alpha V$ due to operators (2), it contains also small admixture of ordinary neutrinos. Each decay produces monoenergetic neutrinos N_x with energies $E_a = \frac{1}{2}M_\Delta(1 - M_a^2/M_\Delta^2)$, where M_0 is the mass of ρ^- meson and $M_{1,2,\dots}$ are the masses of its excitations. In Fig. 2(a) the spectrum of neutrinos produced by decay of galactic dark matter is shown by sharp peaks (solid blue) for

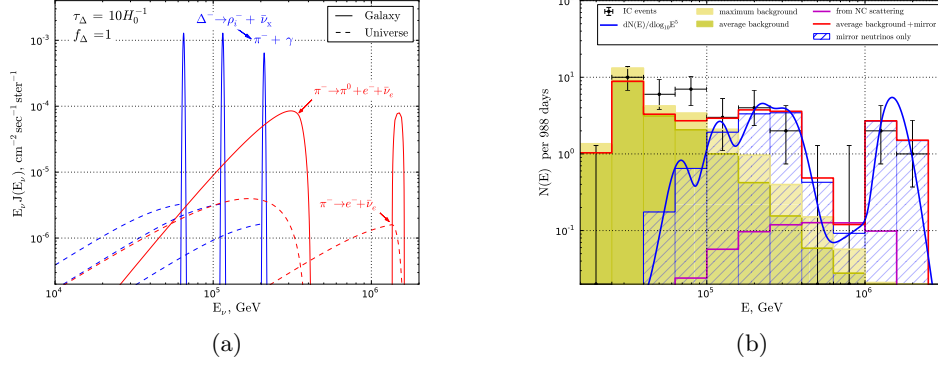


Figure 2. – (a) Shadow neutrino spectrum produced by Δ -barion decay and subsequent decay of shadow pions (b) Spectrum of VHE neutrino events as predicted in our model.

M_0, M_1, M_2 respectively being 3.0, 3.1 and 3.2 PeV. Due to close degeneracy between the masses of Δ -baryon and ρ_a^- mesons, the neutrino energies are $E_a \ll 1$ PeV while the most of initial energy $= M_\Delta$ is taken away by mesons ρ_a^- .

Vector mesons promptly decay into mirror pion and photon, $\rho_a^- \rightarrow \pi^- + \gamma'$, and subsequent decay of the pion produces the neutrino once again (solid red curves in Fig. 2(a)). Shadow π^- has two decay modes, two body $\pi^- \rightarrow E \bar{N}_E$ and three body $\pi^- \rightarrow \pi^0 E \bar{N}_E$. Interestingly, their branching ratios are comparable which fact is intimately related to the value $\Lambda' \sim 100$ TeV [2]. Two body decay produces neutrinos with a narrow energy spectrum concentrated around $M_\Delta/2 \simeq 1.6$ PeV, while the three body decay, due to smaller phase space, produces less energetic neutrinos with a wide spectrum extending up to the value $E_{\max} = M_- - M_0 - M_E \simeq M_U - M_D - M_E \simeq 0.4$ PeV.

Fig. 2(a) shows the final spectrum including the neutrinos produced by the decay of dark matter in the galactic halo, and extragalactic neutrinos produced by the decay of cosmological dark matter at large redshifts. The fraction of extragalactic neutrinos strongly depends on the decay time τ_Δ (in Fig. 2 we take $\tau_\Delta = 10 t_U$). Fig. 2(b) shows how such a spectrum will be seen by the IceCube provided that active-shadow neutrino mixing angles are order 10^{-5} . Here the effective areas for the neutrino detection by IceCube [1] and characteristic error bars in estimation of neutrino energies (of about 13%) are taken into account. Needless to say, that the obtained spectrum of events look very much like the spectrum observed by the IceCube [1]. The validity of our model will be tested with increasing statistics by the IceCube collaboration.

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